

A Community Terrain-Following Ocean Modeling System (ROMS/TOMS)

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Award Number: N00014-10-1-0322

<http://ocean-modeling.org> <http://www.ocean-modeling.org>

LONG-TERM GOALS

The long-term technical goal is to design, develop and test the next generation, primitive equation ocean model for high-resolution scientific (ROMS: Regional Ocean Modeling System) and operational (TOMS: Terrain-following Ocean Modeling System) applications. This project will improve the ocean modeling capabilities of the U.S. Navy for relocatable, coastal, coupled atmosphere-ocean forecasting applications. It will also benefit the ocean modeling community at large by providing the current state-of-the-art knowledge in physics, numerical schemes, and computational technology.

OBJECTIVES

The main objective is to produce a tested expert ocean-modeling framework for scientific and operational applications over a wide range of spatial (coastal to basin) and temporal (days to seasons) scales. The primary focus is to implement the most robust set of options and algorithms for relocatable coastal forecasting systems nested within basin-scale operational models for the Navy. The system includes some of the analysis and prediction tools that are available in Numerical Weather Prediction (NWP), such as: 4-dimensional variational data assimilation (4D-Var), ensemble prediction, adaptive sampling, and circulation stability and sensitivity analysis.

APPROACH

The structure of TOMS is based on ROMS because of its accurate and efficient numerical algorithms, tangent linear and adjoint models, variational data assimilation, modular coding and explicit parallel structure conformal to modern computer architectures (both cache-coherent shared-memory and distributed cluster technologies). Currently, both ROMS and TOMS are identical and continue improving and evolving. ROMS remains as the scientific community model while TOMS becomes the operational community model.

ROMS/TOMS is a three-dimensional, free-surface, terrain-following ocean model that solves the Reynolds-averaged Navier-Stokes equations using the hydrostatic vertical momentum balance and Boussinesq approximation (Haidvogel *et al.* 2000, 2008; Shchepetkin and McWilliams, 2005, 2009). The governing dynamical equations are discretized on a vertical coordinate that depends on the local water depth. The horizontal coordinates are orthogonal and curvilinear allowing Cartesian, spherical,

Report Documentation Page			Form Approved OMB No. 0704-0188	
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1. REPORT DATE 2010	2. REPORT TYPE	3. DATES COVERED 00-00-2010 to 00-00-2010		
A Community Terrain-Following Ocean Modeling System (ROMS/TOMS)			5a. CONTRACT NUMBER	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Rutgers University, Institute of Marine and Coastal Sciences, 71 Dudley Road, New Brunswick, NJ, 08901-8521			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)	
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT				
15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 11
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified		

and polar spatial discretization on an Arakawa C-grid. Its dynamical kernel includes accurate and efficient algorithms for time-stepping, advection, pressure gradient (Shchepetkin and McWilliams 2003, 2005), several subgrid-scale parameterizations (Durski *et al.*, 2004; Warner *et al.*, 2005) to represent small-scale turbulent processes at the dissipation level, and various bottom boundary layer formulations to determine the stress exerted on the flow by the bottom.

Several adjoint-based algorithms exist to explore the factors that limit the predictability of the circulation in regional applications for a variety of dynamical regimes (Moore *et al.*, 2004, 2009). These algorithms use the ideas of Generalized Stability Theory (GST) in order to identify the most unstable directions of state-space in which errors and uncertainties are likely to grow. The resulting singular vectors can be used to construct ensembles of forecasts by perturbing initial and boundary conditions (optimal perturbations) and/or perturbing surface forcing (stochastic optimals). Perturbing the system along the most unstable directions to the state-space yields information about the first (ensemble mean) and second (ensemble spread) moments of the probability density function. Given an appropriate forecast skill measure, the circulation is predictable if low spread and unpredictable if large spread.

ROMS/TOMS uniquely supports three different 4D-Var data assimilation methodologies (Moore *et al.*, 2010a, b): a primal form of the incremental strong constraint 4D-Var (I4D-Var), a strong/weak constraint dual form of 4D-Var based on the Physical-space Statistical Analysis System (4D-PSAS), and a strong/weak constraint dual form of 4D-Var based on the indirect representer method (R4D-Var). In the dual formulations, the search for the best ocean circulation estimate is in the subspace spanned only by the observations, as opposed to the full space spanned by the model as in the primal formulation. Although the primal and dual formulations yield identical estimates of the ocean circulation for the same *a priori* assumptions, there are practical advantages and disadvantages to both approaches (Moore *et al.*, 2010a, b, c). To our knowledge, ROMS/TOMS is the only open-source, ocean community-modeling framework supporting all these variational data assimilation methods and other sophisticated adjoint-based algorithms.

There are several biogeochemical models available in ROMS. In order of increasing ecological complexity these include three NPZD-type models (Franks *et al.*, 1986; Powell *et al.*, 2006; Fiechter *et al.*, 2009), a nitrogen-based ecosystem model (Fennel *et al.*, 2006, 2008), a Nemuro-type lower level ecosystem model (Kishi *et al.*, 2007), and a bio-optical model (Bissett *et al.*, 1999).

ROMS includes a sediment-transport model with an unlimited number of user-defined cohesive (mud) and non-cohesive (sand) sediment classes (Warner *et al.*, 2008). Each class has attributes of grain diameter, density, settling velocity, critical stress threshold for erosion, and erodibility constant. A multi-level bed framework tracks the distribution of every size class in each layer and stores bulk properties including layer thickness, porosity, and mass, allowing the computation of bed morphology and stratigraphy. Also tracked are bed-surface properties like active-layer thickness, ripple geometry, and bed roughness. Bedload transport is calculated for mobile sediment classes in the top layer.

ROMS is a very modern and modular code written on F90/F95. It uses C-preprocessing to activate the various physical and numerical options. The parallel framework is coarse-grained with both shared-memory (OpenMP) and distributed-memory (MPI) paradigms coexisting in the same code. Because of its construction, the parallelization of the adjoint is only available for MPI. Several coding standards have been established to facilitate model readability, maintenance, and portability. All the state model variables are dynamically allocated and passed as arguments to the computational routines via

dereferenced pointer structures. All private arrays are automatic; their size is determined when the procedure is entered. This code structure facilitates computations over nested grids. There are three types of nesting capabilities in ROMS: (i) *refinement* grids which provide increased resolution (3:1 or 5:1) in a specific region; (ii) *mosaics* which connect several grids along their edges, and (iii) *composite* grids which allow overlap regions of aligned and non-aligned grids.

WORK COMPLETED

After a complete overhaul of the ROMS/TOMS 4D-Var data assimilation capabilities in FY09, we concentrated in FY10 to develop and test additional algorithms for 4D-Var observations impact, observations sensitivity, array modes, and posterior error covariance analysis. Some of these developments required the adjoint of the 4D-Var data assimilation system, denoted as $(4D\text{Var})^T$. Currently, $(4D\text{Var})^T$ is only available for the dual formulation algorithms 4D-PSAS and R4D-Var because the adjoint of the Lanczos-based, conjugate gradient algorithm used in the minimization is much simpler. This capability is challenging in I4D-Var due to the complexity of the I/O intensive, Lanczos-based, conjugate gradient and preconditioning algorithms that are used when the minimization is carried out in model space. We are planning to build the $(I4D\text{-Var})^T$ in the future. The observation impact algorithm can be used to quantify the contribution of each observation during a 4D-Var analysis to a specified aspect (scalar function, say \mathbf{I}) of the ocean circulation (Langland and Baker, 2004; Gelaro and Zhu, 2009; Trémolet, 2008; Moore *et al.*, 2010c). That is, it identifies the part of the model space that controls \mathbf{I} and that is activated by the observations. It yields the actual contribution of each observation to the circulation increment.

The observation sensitivity is based on $(4D\text{-Var})^T$ and quantifies the change that would result in the circulation estimate as result of changes in the observations or observation array (Trémolet, 2008; Moore *et al.*, 2010c). It is a very useful tool for efficient generation of observation system experiments (OSEs), observation array design, and adaptive sampling. It also can be used to predict the changes that will occur in \mathbf{I} in the event of a platform failure or a change in the observation array (Moore *et al.*, 2010c).

The array modes of the stabilized representer matrix can be used to determine the most stable component of the circulation with respect to changes in the innovation vector (Bennett, 1985; Moore *et al.*, 2010c). The array modes are independent of the observation values and depend only on the observation locations, the *prior* covariances, and *prior* circulation.

Substantial work has been carried out in the nesting capabilities of ROMS/TOMS. Currently, we are migrating this development from our research branches to the distributed, official version of the model. The kernel of the nonlinear, tangent linear, representer, and adjoint models has been updated to allow different I- and J- ranges in DO-loops to permit operations on various nested grid classes (refinement, mosaics, and composite) and nesting layers (refinement and composite grid combinations). This development is very delicate and requires a lot of testing. We have been developing this capability for couple of years and will be available soon to the user community and released as ROMS 4.0.

We held a very successful workshop at the Hawaii Imin International Conference Center, University of Hawaii at Manoa, Honolulu, Hawaii, April 5-8, 2010 (<http://www.myroms.org/2010workshop>). As in the past, several tutorials were offered about basic and advanced ROMS algorithms.

We also organized a 4D-Var data assimilation workshop for advanced ROMS users at the Simularium, Baskin School of Engineering, University of California Santa Cruz, Santa Cruz, CA, July 12-16, 2010 (http://www.myroms.org/4DVar_workshop_2010). It included tutorial style lectures on 4D-Var data assimilation methodology, algorithms, and hands-on exercises. By the end of the week, users were running their own application. This was our first workshop of this kind and serves as a prototype for similar workshops in the future.

RESULTS

A comprehensive documentation material was developed for the 4D-Var data assimilation workshop held at University of California Santa Cruz in July 2010. The lectures, tutorial, and exercise are available to everyone in [WikiROMS](#), as shown in Figure 1.

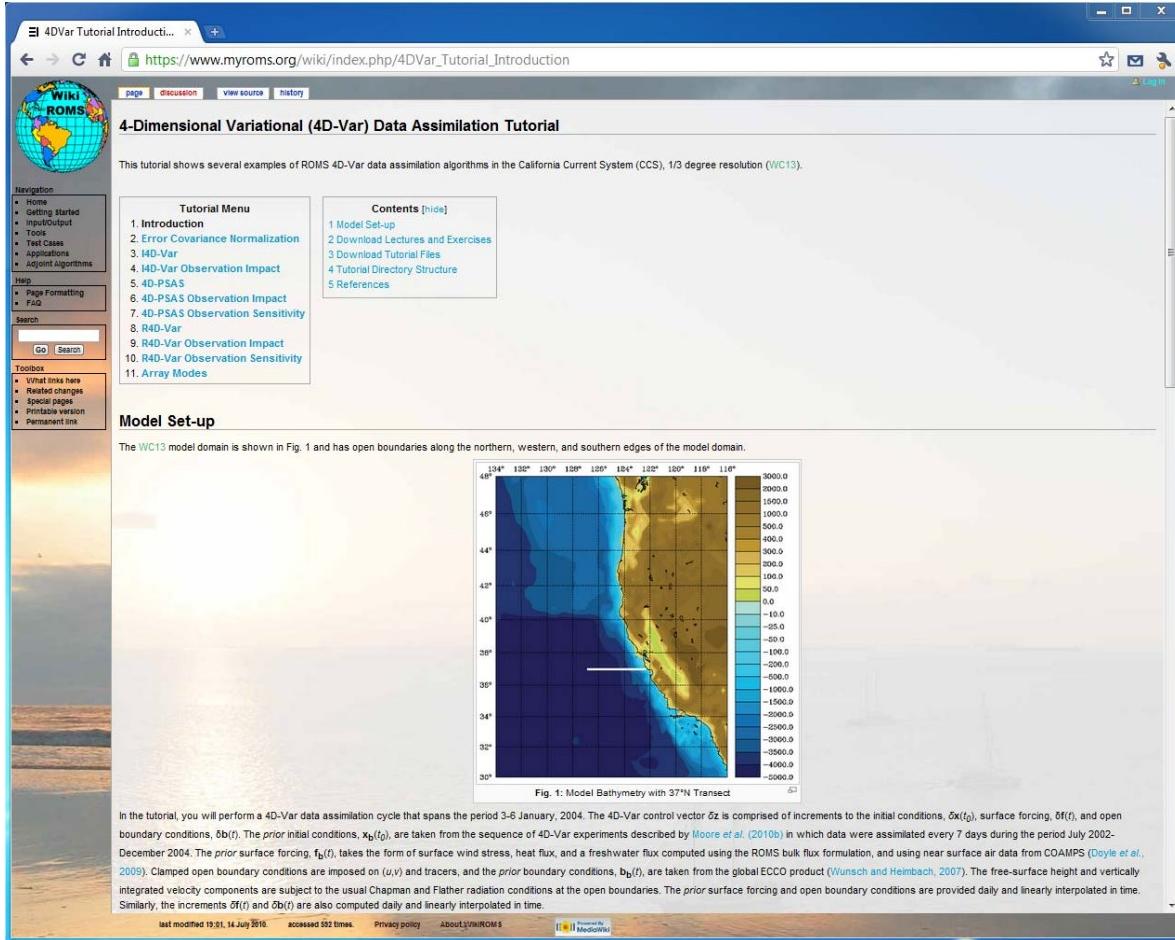


Figure 1: Screenshot of WikiROMS 4D-Var data assimilation tutorials showing downloadable PDF links for lectures, tutorials, and exercises. It includes pages for 1) Introduction, 2) Error Covariance Normalization, 3) I4D-Var, 4) I4D-Var Observation Impact, 5) 4D-PSAS, 6) 4D-PSAS Observation Impact, 7) 4D-PSAS Observation Sensitivity, 8) R4D-Var, 9) R4D-Var Observation Impact, 10) R4D-Var Observation Sensitivity, and 11) Array Modes.

A realistic ROMS application for the U.S. west coast and the California Current System (CCS) is provided in the tutorials to run all the 4D-Var algorithms introduced during the lectures. This configuration is referred to as WC13. It has 10 km horizontal resolution and 30 levels in the vertical. While 30 km resolution is inadequate for capturing much of the energetic circulation associated with the CCS, WC13 captures the broad scale features of the circulation quite well, and serves as a very useful and efficient illustrative example for the various 4D-Var data assimilation algorithms in the tutorials for the period of Jan 3-6, 2004.

The 4D-Var control vector $\delta\mathbf{z}$ is comprised of increments to the initial conditions, $\delta\mathbf{x}(t_0)$, surface forcing, $\delta\mathbf{f}(t)$, and open lateral boundary conditions, $\delta\mathbf{b}(t)$. The *prior* initial conditions, $\mathbf{x}_b(t_0)$, are taken from the sequence of 4D-Var experiments described by Moore *et al.* (2010b) in which data were assimilated every 7 days during the period July 2002- December 2004. The *prior* surface forcing, $\mathbf{f}_b(t)$, takes the form of surface wind stress, heat flux, and a freshwater flux computed using the ROMS bulk flux formulation, and using near surface air data from COAMPS (Doyle *et al.*, 2009). Clamped open boundary conditions are imposed on (u,v) and tracers, and the *prior* lateral open boundary conditions, $\mathbf{b}_b(t)$, are taken from the global ECCO product (Wunsch and Heimbach, 2007). The free-surface height and vertically integrated velocity components are subject to the usual Chapman and Flather radiation conditions at the open boundaries. The *prior* surface forcing and lateral open boundary conditions are provided daily and linearly interpolated in time. Similarly, the increments $\delta\mathbf{f}(t)$ and $\delta\mathbf{b}(t)$ are also computed daily and linearly interpolated in time.

The observations assimilated into the model are satellite SST, satellite SSH in the form of a gridded product from Aviso, and hydrographic observations of temperature and salinity collected from Argo floats and during the GLOBEC/LTOP and CalCOFI cruises off the coast of Oregon and southern California, respectively. The observation locations are illustrated in Figure 2.

The majority of the observations available for assimilation in the ocean are from satellite platforms in the form of SSH and SST. The analysis of Moore *et al.* (2010b) found that less than 10% of the available satellite observations provide independent information. There is a lot of observation redundancy which increases with model horizontal resolution.

Figure 3, shows the observation impact and observation sensitivity for a 3 day R4D-Var data assimilation cycle on the time-averaged transport across 37N over the upper 500m, denoted by I_{37N} , and given by:

$$I_{37N}(\mathbf{X}) = \frac{1}{N} \sum_{i=1}^N \mathbf{h}^T \mathbf{X}_i$$

where \mathbf{h} is a vector with non-zero elements corresponding to the velocity grid points that contribute to the transport normal to the 37N section shown in Figure 2, N is the number of time steps during the assimilation interval, and \mathbf{X}_i is the model state vector at time $i \Delta t$. Figure 3a shows the total number of observations and number observations per platform used in the observation impact and sensitivity analysis of the transport across 37N. It is clear that the SST is the dominant observation platform followed by SSH. The analysis (Fig. 3b) of the alongshore transport in this upwelling area is influenced primarily by uncertainties in the initial conditions, $\delta\mathbf{x}(t_0)$, and surface forcing, $\delta\mathbf{f}(t)$. Notice that the impact of the CTD and Argo observations on the I_{37N} is significant despite the small

number of these observations (Fig. 3c). The observation sensitivity analysis (Fig. 3d) indicates that I_{37N} will be affected considerably by any changes in the SSH coverage (Moore *et al.*, 2010c).

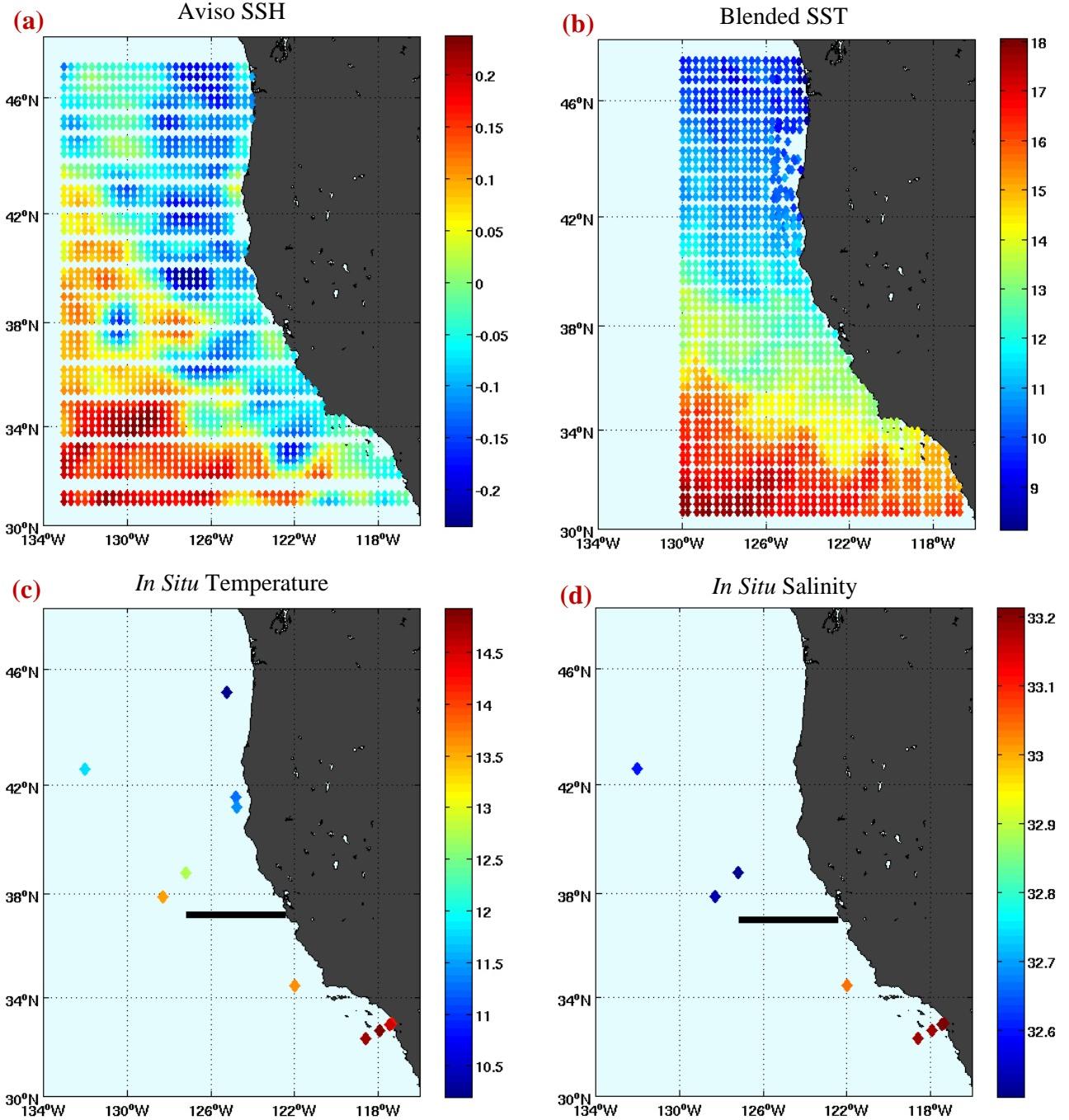


Figure 2: Observations available for 4D-Var data assimilation during the period of Jan 3-6, 2004: (a) Aviso Sea Surface Height (SSH) anomaly, (b) Sea Surface Temperature (SST) daily composite from NOAA PFEG CoastWatch, (c) in situ temperature, and (d) in situ salinity from Argo floats, and GLOBEC/LTOP and CalCOFI cruises.

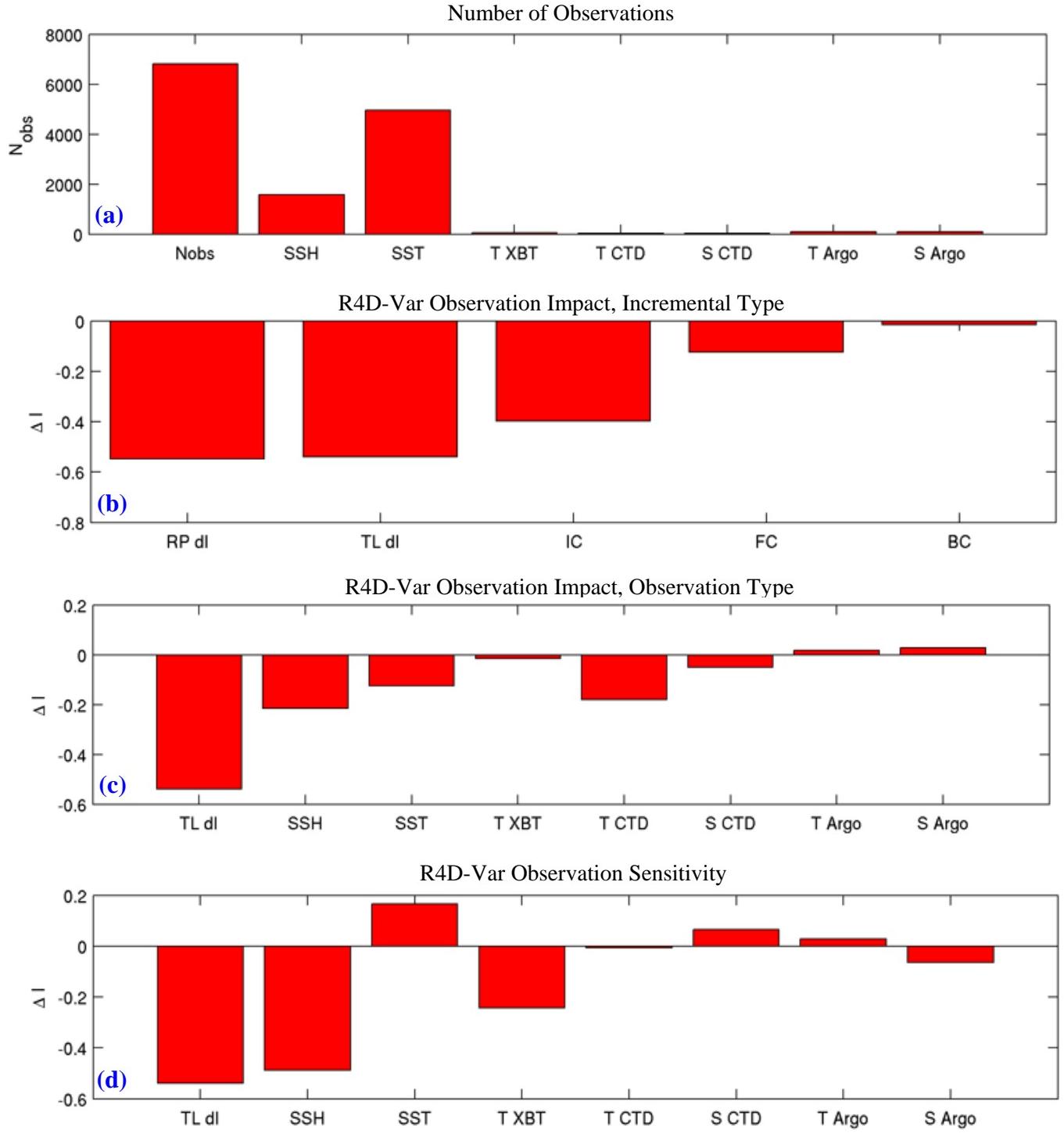


Figure 3: 4D-Var observation impact and sensitivity for the transport across 37N: (a) total number of observations and number of observations per platform used in the observation impact and observation sensitivity analyses, (b) total transport increment ΔI_{37Nz} (Sv) and increments associated with initial conditions, surface forcing, and lateral boundary conditions, (c) same as (b) except that the bars indicate the contributions from each observing platform, and (d) same as (c) except but the observation sensitivity using $(4D\text{-}Var)^T$.

IMPACT/APPLICATIONS

This project will provide the ocean modeling community with a freely accessible, well documented, open-source, terrain-following, ocean model for regional nowcasting and forecasting that includes advanced data assimilation, ensemble prediction, and analysis tools for adaptive sampling and circulation dynamics, stability, and sensitivity.

TRANSITIONS

The full transition of ROMS/TOMS to the operational community is likely to occur in the future. However, the ROMS/TOMS algorithms are now available to the developers and scientific and operational communities through the website <http://www.myroms.org/>.

RELATED PROJECTS

The work reported here is related to other already funded ONR projects using ROMS. In particular, the PI (H. Arango) closely collaborates with A. Moore (adjoint-based algorithms) at University of California, Santa Cruz, A. Miller and B. Cornuelle (ROMS adjoint and variational data assimilation) at Scripps Institute of Oceanography, E. Di Lorenzo (Southern California predictability) at Georgia Institute of Oceanography, and J. Wilkin (Mid-Atlantic Bight variational data assimilation) at Rutgers University.

The PI is also supported by the following grants:

“Characterization and Modeling of the Philippine Archipelago Dynamics Using the ROMS 4DVAR Data Assimilation System”, grant number N00014-04-1-0417, <http://www.myroms.org/philex>.

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